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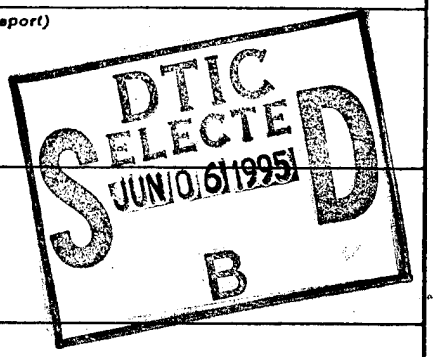

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Studies of the 29 possible candidates to use as the working medium of a gamma ray laser have identified the 31-year isomer of Hafnium-178 as the best. This research is aimed at the development of a production cycle for this rare substance. A major success of this year's work has been the discovery in byproduct debris from the synthesis of medical isotopes of a quantity of this material equal to 99% of the world's inventory. Chemical conditioning and recovery of this sample have been initiated. Also, an evaluation was made of the 142 reactions with potential for restocking the existing inventories.

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I. Progress in the Conditioning and Acquisition of Samples of $^{178}Hf^{m2}$

As reported last year, the 31-year isomer $^{178}Hf^{m2}$ storing over 1.3 kJ/μg has been identified as the prime candidate for a gamma ray laser[1]. However, despite the great promise of this material, it is very rare because it had never been of interest before. Currently, the production cycles are far from optimized and we have made a number of proposals to improve upon existing approaches. At the present time the only actual source of $^{178}Hf^{m2}$ is Dubna in Russia which makes about 4×10^{14} nuclei per year, a very small amount.

As detailed in last year's report, we discovered that a unique spallation experiment conducted in 1980 at Los Alamos National Laboratory (LASL), while aiming for medical isotopes had incidentally produced[2] an amount of $^{178}Hf^{m2}$ estimated by us to be about 100 years' production from Dubna. Inhibited by a great amount of radioactive debris, the utility of the irradiated target was originally considered to be remote and over the intervening years it was lost from the inventory. Unappreciated was the fact that by 1995 the hazardous byproducts had "aged out" because of their faster decay rates.

We succeeded in locating the spallation target and were instrumental in returning it to the inventory as LASL Target #29-3-1. Some initial uncertainty expressed last year was resolved by the physical aspect of the target. The original spallation experiment had been described[2] as the irradiation of 1 kg of natural Ta by the 800 MeV proton beam from the Los Alamos Meson Physics Facility (LAMPF) for four months during which the target accumulated an integrated exposure of 0.5 to 1.0 Ampere-hour. Now, it is clear that Target #29-3-1 consists of three plates of Ta of about 250 g each containing a concentration of Hf of about 10^{-9}. The remaining 250 g has been located in the form of HDEHP residue which is not conducive to further processing to extract such a small Hf fraction. In any case accountability now exists for all of the original 1980 spallation target.

During the current reporting period we obtained an assay of the Target #29-3-1 reproduced in Fig. 1. The spectrum shown there proves the substantial content of $^{178}Hf^{m2}$ that is consistent with the initial estimate of somewhat over 10^{17} nuclei. The initial population has decayed by about one half of a halflife and Target #29-3-1 represents 75% of the mass originally subjected to the spallation reactions. The data of Fig. 1 correspond to 4.5×10^{16} isomers of $^{178}Hf^{m2}$. As shown in the figure, the activity of the isomeric content is only 0.87 mCi while the activity of the Hf fraction is 20 mCi. Integrated together the noise from other species is a dangerous 100 Ci.

To be useful for the pumping experiments necessary to prove feasibility of dumping the stored energy, the dangerous level of background radioactivity must be removed. Since the fraction which is chemically Hf has an activity of only 20 mCi, chemical separation of the Hf parts from the unreacted Ta is an attractive but difficult option. The sole source of the service needed was determined to be LASL and they were contracted to extract and deliver the entire Hf fraction from Target #29-3-1. The hazards involved necessitated their upgrading of the handling facility and that is introducing delay in the completion of the task. Delivery is

projected for the end of 1995.

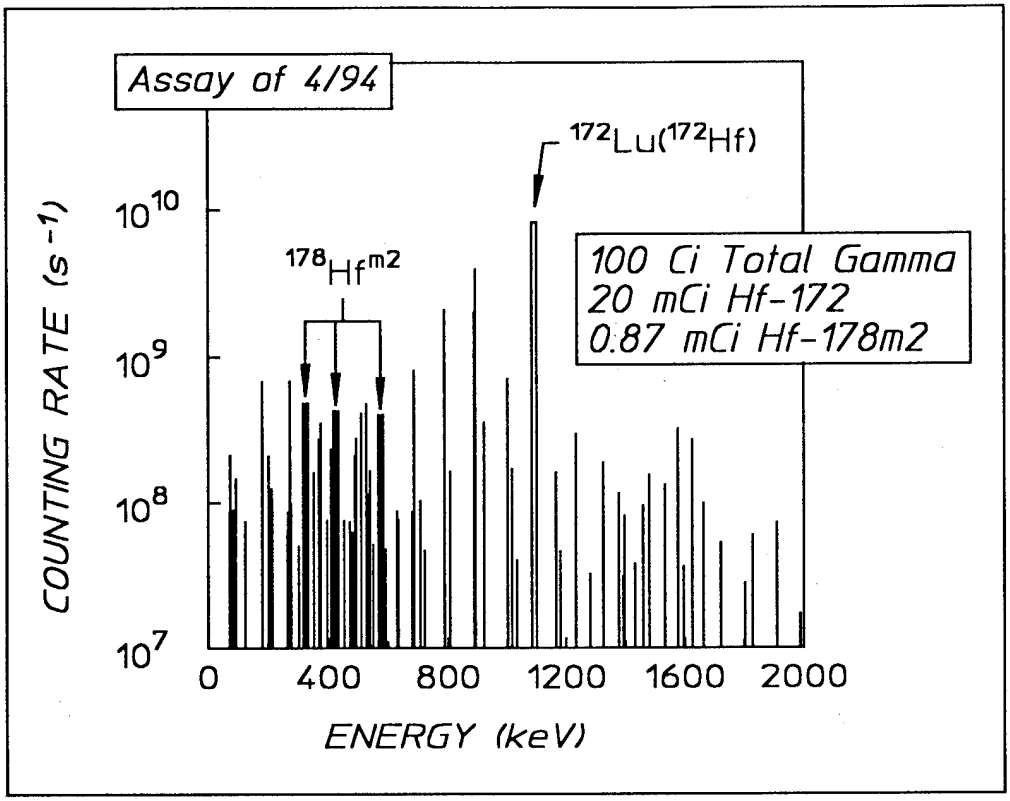

Figure 1: Spectrum of the LASL spallation Target #29-3-1 taken in April 1994.

II. Survey of Nuclear Reactions Leading to the Production of $^{178}Hf^{m2}$

Both of the demonstrated fuel cycles for the production of the 31-year isomer of hafnium, $^{178}Hf^{m2}$ challenge strategies for the production of the amounts of this unique material that might be needed by end-users. The nuclear reaction $^{176}Yb(\alpha,2n)^{178}Hf^{m2}$ is clean but slow, while the more robust spallation process needs considerable optimization to suppress the collateral production of undesirable byproducts. There is a very clear need for a "magic bullet" in the form of a reaction for the production of commercial amounts of the hafnium isomer at reasonable scales of investment without the generation of noxious byproducts that are hazardous to remove and difficult to destroy.

During this reporting period a theoretical physicist having had long experience with γ-ray laser problems, Dr. S. Olariu served as a consultant charged with the task of collecting a

definitive survey of all nuclear reactions capable of producing the $^{178}Hf^{m2}$ so that they could be subsequently screened according to practical criteria. The results of that study are reported here. As will seen, there were no "magic bullets" discovered but closure was obtained. It is now clear to about 90% confidence, that spallation offers the best approach. The small uncertainty arises because a few obscure and exotic reactions warrant further consideration, but it is unlikely they will be proven effective. ***It is reasonable to conclude that spallation will be the fuel cycle of choice and efforts to optimize that system should begin.***

In the study reported here 142 nuclear reactions for the production of $^{178}Hf^{m2}$ were analyzed in terms of their economies of angular momenta and energies. The desired product, $^{178}Hf^{m2}$ is distinguished by an unusually large spin of 16$\hbar$ and a relatively high internal energy. While the energy can be obtained from favorably chosen mass defects, the problem of producing a high angular momentum in the product is very difficult.

Basically, a nuclear reaction is a collision in which a projectile hits a target. In the absence of either extraordinary impact parameters for such reactive collisions or massive projectiles, the incident particles must arrive with very large velocities or the targets must already have large spin angular momenta. If massive projectiles are selected, acceleration is difficult; high velocities of incidence imply large kinetic energies that may open many unwanted competing channels for output; and high spin targets are usually comprised of rare isotopes or other spin isomers that are just as hard to fabricate. Translated into quantitative parameters of reaction, these concerns focus attention upon the "excess energies" available for internal excitation of the products and upon the total spin available in the input channel. These quantities were compiled for the 142 reactions capable of producing $^{178}Hf^{m2}$.

II.1 Economies of energy

For the prototypical nuclear reaction,

$$\text{Target} + \text{Projectile} \rightarrow {}^{178}Hf^{m2} + N_\alpha\alpha + N_p p + N_n n \quad , \qquad (1)$$

where α, p, n denote alpha particles, protons, and neutrons, respectively, the threshold energy for the reaction becomes,

$$E_T = \Delta({}^{178}Hf^{m2}) + N_\alpha\Delta_\alpha + N_p\Delta_p + N_n\Delta_n - \Delta_t - \Delta_i \quad , \qquad (2)$$

where the Δ's are the mass excesses given by Lederer et al.,[3] and i denotes a projectile.

If the projectiles are charged, for example because they are protons, then to be able to react they must initially carry an amount of kinetic energy that is more than the potential energy of the Coulomb barrier they will experience in "contact" with the nuclear target. The energy of the Coulomb barrier for each reaction was estimated by the simple expression,

$$E_C = Z_t Z_i / [\, 4\pi\epsilon_0 r_0 (A_t^{1/3} + A_i^{1/3}) \,] \quad , \qquad (3)$$

where A_t , Z_t and A_i , Z_i correspond to the mass and charge of the target and projectile, respectively and $r_0 = 1.3 \times 10^{-15}$ m.

If the projectile is incident with energy E_i , it will have its kinetic energy reduced by E_C before it can enter the nucleus so that only collisions for which $E_i > E_C$ as well as $E_i > E_T$ can lead to a reaction. A typical separation in energy between the threshold and the maximum of an excitation for a reaction is about 5 MeV, so an optimum energy of incidence could be reasonably estimated by,

$$E_i = \text{Maximum} (E_C , E_T) + 5 \text{ MeV} \quad . \qquad (4)$$

Tabulation of the values of E_i for each of the candidate reactions for the production of $^{178}Hf^{m2}$ was an essential step in the screening for high yields. At the peak of the excitation function for a reaction the "excess" energy of excitation will determine the yield of a particular product. Because it is the internal energy of excitation of the intermediate reaction complex, it determines what output channels can be entered while still conserving energy. This excitation energy, E_E can be computed,

$$E_E = E_i - E_T \quad . \qquad (5)$$

The excitation energy needs to be greater than the 2.5 MeV needed to reach the 31-year isomeric state. To a point excitation above the bare minimum increases the yield. However, since the final state density for the emission of a free particle in the output channel is so much greater, if there is enough internal energy to permit the evaporation of an additional particle from the complex beyond those modeled in Eq. (1) then that channel will become dominant as energy is increased. Competition from the free-particle channel will then strongly reduce yield in the desired output channel in which the particle must be retained to give the total mass of the isomer. In practice this means that for screening,

$$2.5 \text{ MeV} < E_E < 10 \text{ MeV} \quad , \qquad (6)$$

the 10 MeV representing the energy at which there is significant evaporation from virtually all reaction complexes.

II.2 Economies of angular momentum

Were the energetics optimized, at the maximum of the excitation function a reaction such as (α,2n) would typically display a cross section of about 1000 mb. However, even when optimized at Dubna by Oganessian *et al.*[4] the reaction $^{176}Yb(\alpha,2n)^{178}Hf^{m2}$ was found to have a cross section of only about 10 mb. The smaller magnitude can be understood to be a consequence of the large total angular momentum that must be available in the input channel in order to produce a product with spin 16$\hbar$. At moderate energies this reaction does have sufficient maximum angular momentum available, but the characteristic cross section is still attenuated by a couple of orders of magnitude because the output channel to the ground state

remains more favorable. Had the channel spin been inadequate to excite the 16ħ needed to populate the isomer, the reaction cross section would have been much more strongly attenuated or simply forbidden. As can be appreciated, the total spin angular momentum available in the input channel can be as important as the incident energy in screening potential reactions for the production of the $^{178}Hf^{m2}$.

In the survey reported here the maximum orbital angular momentum of the incident particle was estimated by the expression:

$$L_{max} = (2A_i u E_i)^{1/2} r_0 (A_t^{1/3} + A_i^{1/3}) \quad , \qquad (7)$$

where $u = 1.66 \times 10^{-27}$ kg is the atomic mass unit. The maximum input channel spin occurs for the parallel coupling of L_{max} with the target spin, I_t so that,

$$S = L_{max} + I_t \quad . \qquad (8)$$

For candidates to be at least as good as the Dubna reaction, $S \geq$ about 20. Were it possible to increase the channel spin to a value much in excess of the total spin of the products, so that $S >> 20$, the cross section for the isomer would approach that for production of the ground state ^{178}Hf.

II.3 Potential reactions - Tabulations and scoring

Systematics show that in the mass region of $Z \sim 72$ cross sections are reduced by about an order of magnitude for each free charged particle emerging among the products. This suggests that reactions be arranged in order of the total atomic number in the input channel, $Z_T = Z_i + Z_t$. Reactions for which $Z_T = 72$ would require the emission of no charged particle to produce $^{178}Hf^{m2}$ because Hf has $Z = 72$, and so would offer the potential for maximal cross sections if it could be also arranged for $S >> 20$. The reactions for $Z_T = 72$ are summarized in Table I.

Reactions for which $Z_T = 73$ must emit one proton among the products so that $Z = 72$ will remain to form Hf. These reactions are summarized in Table II, while the analogous compilation for total input charge of $Z_T = 74$ appears in Table III.

For the purposes of screening the 142 reactions reported in the tables a rough but usable approximation can be constructed by degrading the cross section by one order of magnitude for each free proton necessary among the products while increasing it by as much as two orders in proportion to the extent to which $S >> 20$. Normalizing to 1000 mb for the production of low-spin ground states and to the 10 mb for the Dubna reaction gives a coarse scale, where ΔZ is the number of orders of magnitude caused by excess protons in the input channel and ΔS is the number of orders enhanced by a very large channel spin,

Cross section (mb)	$\Delta Z + \Delta S$
1000	0 + 2
100	-1 + 2, 0 + 1
10	-2 + 2, -1 + 1, (0 + 0)
1	-3 + 2, -2 + 1, -1 + 0

with the term in parentheses identifying the Dubna reaction which can be perceived as losing no potential cross section because of a need to emit free charges while having sufficient channel spin S ~ 20 to avoid being forbidden, but not enough for enhancement. With this scale of measure the 142 reactions were arranged to identify the most promising on the basis of cross section and were then evaluated for their practicality and potential cost.

II.4 Conclusions

The approximate scale of estimated cross sections indicates that if there are any 1000 mb reactions for the production of $^{178}Hf^{m2}$ they are "0 + 2" reactions which, because of the $\Delta Z = 0$, are to be found in Table I. While reactions such as $^{160}Gd(^{18}O,\gamma')^{178}Hf^{m2}$ clearly conform to the "0 + 2" pattern, the excess energy $E_E >> 10$ MeV is in violation of the requirement of Eq. (6); meaning that the yield of isomers will be greatly reduced or even precluded by the availability of output channels involving the evaporation of additional neutrons. The $^{160}Gd(^{18}O,\gamma')$ reaction will not really produce $^{178}Hf^{m2}$. In the analogous manner all of the remainder of the "0 + 2" reactions can be eliminated because of the great excess of internal energy in the products.

In a search for 100 mb reactions, those conforming to the "0 + 1" pattern must be eliminated for the same reasons as the "0 + 2" reactions. Even to obtain modest channel spins in excess of 20 requires the concomitant production of excess internal energy that would direct all of the yield into competing output channels associated with the evaporation of neutrons. However, the alternative "-1 + 2" reactions are not completely eliminated by the same considerations. The reactions for which $\Delta Z = -1$ are found in Table II. In this case most of the potential systems for which $S >> 20$ are precluded by an excess of residual excitation energy, but there are two exceptions, $^{176}Yb(^{7}Li,p4n)^{178}Hf^{m2}$, and $^{177}Lu^{m}(\alpha,p2n)^{178}Hf^{m2}$. As can be seen, the channel spins are very favorable with 34$\hbar$ and 33$\hbar$ units of angular momentum being available, respectively, while the excess internal energies of excitation are only 7.7 MeV and 5.0 MeV, respectively. It is interesting that the analogous reaction with a ^{6}Li projectile on ^{176}Yb is eliminated because of the much larger residual internal energy of 15.4 MeV.

Searching for 10 mb reactions from Tables I, II, and III for the patterns "0 + 0"," -1 + 1", and "-2 + 2", respectively gives one, one, and six reactions respectively. The results of these searches can be conveniently summarized as follows:

Reaction	Possible cross section (mb)	ΔZ
$^{176}Yb(^{7}Li,p4n)^{178}Hf^{m2}$	100	-1
$^{177}Lu^{m}(\alpha,p2n)^{178}Hf^{m2}$	100	-1
$^{176}Yb(\alpha,2n)^{178}Hf^{m2}$	10*	0
$^{176}Lu(\alpha,pn)^{178}Hf^{m2}$	10	-1
$^{182}Hf(\alpha,2p6n)^{178}Hf^{m2}$	10	-2
$^{179}Hf(\alpha,2p3n)^{178}Hf^{m2}$	10	-2
$^{177}Lu^{m}(^{7}Li,2p4n)^{178}Hf^{m2}$	10	-2
$^{176}Lu(^{7}Li,2p3n)^{178}Hf^{m2}$	10	-2
$^{177}Lu^{m}(^{6}Li,2p3n)^{178}Hf^{m2}$	10	-2
$^{176}Yb(^{9}Be,2p5n)^{178}Hf^{m2}$	10	-2

where all reactions rigorously satisfy Eq. (6) except for the two for which 10 MeV $< E_E <$ 11 MeV which is still within the spirit of the approximations of Eq. (6) and where the * identifies the Dubna reaction.

Considerations of the practicality of each of the eight reactions by even the most basic standards serve to eliminate most of them. For practical levels of operation of any accelerator it is unlikely that the concentration of the product $^{178}Hf^{m2}$ isomer can be brought above 1 ppm (10^{-6}) so it will be necessary to chemically separate the product from the unreacted diluent. This means that the target nuclei can not belong to the same Hf element as the product, thus effectively eliminating the reactions based upon feedstocks of hafnium. Attempts to use isomeric target nuclei such as $^{177}Lu^{m}$ pose a double problem. The isomeric nature of the target means that it too must be produced by some challenging means. In the case of $^{177}Lu^{m}$ there is the option for neutron capture from ^{176}Lu, a reaction which has a cross section of only 7b and requires the isotopic separation of natural Lu to prepare a target of the ^{176}Lu which has an abundance of only 2.6%. Moreover, when finally produced the isomeric target $^{177}Lu^{m}$ then has a specific activity of 4.6 kCi / g, making it extremely hazardous to use in subsequent bombardment to produce $^{178}Hf^{m2}$. It seems that the two reactions with isomeric Lu targets can be eliminated. The remaining reactions are:

Reaction	Possible cross section (mb)	ΔZ	S
$^{176}Yb(^{7}Li,p4n)^{178}Hf^{m2}$	100	-1	34
$^{176}Yb(\alpha,2n)^{178}Hf^{m2}$	10*	0	21
$^{176}Lu(\alpha,pn)^{178}Hf^{m2}$	10	-1	28
$^{176}Lu(^{7}Li,2p3n)^{178}Hf^{m2}$	10	-2	41
$^{176}Yb(^{9}Be,2p5n)^{178}Hf^{m2}$	10	-2	47

Beyond this point attempts to rank the reactions further become quite speculative.

Possibly the strongest remaining factor is feedstock cost. Because of its low relative abundance, reasonably separated ^{176}Lu sells for $200,000 per gram while ^{176}Yb is about $8,000. If the channel spin of 28 for the third reaction is large enough to score as +2 instead of +1 order of magnitude as assumed, then the cross section could be as much as 100 mb meaning that only 10% as much ^{176}Lu would be needed to produce the same yield and that would justify a tenfold larger cost in comparison to the ^{176}Yb. Per unit yield, this might make the target cost comparison be $20,000 to $8,000 which brings it into the range where optimizing production efficiencies and chemistries could reverse the apparent favorableness of the ^{176}Yb.

Generally, simpler projectiles admit higher beam currents so it might be reasonable to favor α particles over light nuclei. It is clear why the Dubna reaction would be initially favored, but it is not so sure that either ^{176}Yb(^{7}Li,p4n)^{178}Hf^{m2} with the higher cross section, favorable feedstock, but lowered beam current of ^{7}Li; and ^{176}Lu(α,pn)^{178}Hf^{m2} with the possibly higher cross section from the channel spin, the most favorable projectile, but more costly feedstock might not prove better than the Dubna reaction upon comparative study. ***However, it seems unlikely that even in the best circumstances the improvement could be more than a factor of ten.***

The existing spallation sample represents about 100 years production at the rate at which the Dubna reaction is currently employed. Should study and optimization of the two possible alternatives succeed to the maximum extent possible, it seems that the time required for restocking the spallation sample would drop only to 10 years. It seems a reasonable conclusion that there is probably more to gain by concentrating upon optimizing the spallation yield then upon any of the 142 reactions considered in this work.

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Table I

Production of (31-yr) Hf-178

Reactions having total input charge = 72

Reaction Target	Projectile	Emission	Target spin	Threshold energy (MeV)	Coulomb barrier (MeV)	Projectile energy (MeV)	Internal E of excitation (MeV)	Orbital momentum L-max	Channel spin h-bar	Abundanc %
Hf-177	n	*gamma*	3.5	-5.17	0					18.6
Hf-178	n	n	0	2.45	0	7.45	5.0	5.1	5.1	27.1
Hf-179	n	2n	4.5	8.55	0	13.5	5.0	6.9	11.4	13.7
Hf-180	n	3n	0	15.9	0	20.9	5.0	8.6	8.6	35.2
Hf-182	n	5n	0	28.3	0	33.9	5.6	11	11	U
Lu-177m	p	*gamma*	11.5	-5.85	11.8	16.8	22.7	7.7	19.2	U
Lu-176	d	*gamma*	7	-9.73	11.4	16.4	26.1	11.2	18.2	2.61
Lu-176	t	n	7	-3.48	11.1	16.1	19.6	13.9	20.9	2.61
Lu-175	t	*gamma*	3.5	-9.77	11.1	16.1	25.9	13.9	17.4	97.3
Yb-176	*alpha*	2n	0	17.2	21.5	26.5	9.3	21	21	12.6
Yb-176	He-3	n	0	-3.35	22	27	30.4	18	18	12.6
Yb-174	*alpha*	*gamma*	0	4.54	21.6	26.6	22.1	21	21	31.6
Er-170	Be-9	n	0	6.85	39.5	44.4	37.6	43.4	43.4	14.9
Gd-160	O-18	*gamma*	0	18.7	70.4	75.4	56.7	84.5	84.5	21.8
Te-130	Ca-48	*gamma*	0	81.5	132.4	137.4	55.9	201.3	201.3	34.5

Dubna Reaction

Table II

Production of (31-yr) Hf-178

Reactions having total input charge = 73

Reaction Target	Projectile	Emission	Target spin	Threshold energy (MeV)	Coulomb barrier (MeV)	Projectile energy (MeV)	Internal E of excitation (MeV)	Orbital momentum L-max	Channel spin h-bar	Abundanc %
Ta-180	n	p2n	8	14.1	0	19.2	5.1	8.3	16.3	0.012
Ta-181	n	p3n	3.5	21.8	0	26.8	5.0	9.8	13.3	99.98
Hf-182	p	p4n	0	28.3	11.9	33.3	5.0	10.9	10.9	U
Hf-180	p	p2n	0	15.9	12	20.9	5.0	8.6	8.6	35.2
Hf-179	p	pn	4.5	8.55	12	17	8.5	7.8	12.3	13.7
Hf-178	p	*p gamma*	0	2.45	12	17	14.6	7.8	7.8	27.1
Hf-182	d	p5n	0	30.52	11.5	35.5	5.0	16.6	16.6	U
Hf-180	d	p3n	0	18.1	11.5	23.1	5.0	13.4	13.4	35.2
Hf-179	d	p2n	4.5	10.8	11.5	16.5	5.7	11.2	15.7	13.7
Hf-178	d	pn	0	4.68	11.6	16.6	11.9	11.3	11.3	27.1
Hf-177	d	p	3.5	-2.94	11.6	16.6	19.5	11.3	14.8	18.6
Hf-182	t	p6n	0	36.7	11.2	41.7	5.0	22.6	22.6	U
Hf-180	t	p4n	0	24.4	11.2	29.4	5.0	18.9	18.9	35.2
Hf-179	t	p3n	4.5	17	11.2	22	5.0	16.4	20.9	13.7
Hf-178	t	p2n	0	10.9	11.2	16.2	5.3	14	14	27.1
Hf-177	t	pn	3.5	3.31	11.3	16.3	13.0	14	17.5	18.6
Hf-176	t	p	0	-3.08	11.3	16.3	19.4	14	14	5.2
Lu-177m	*alpha*	p2n	11.5	22.4	21.8	27.4	5.0	21.5	33	U
Lu-176	*alpha*	pn	7	16.3	21.8	26.8	10.5	21.2	28.2	2.61
Lu-175	*alpha*	p	3.5	10	21.9	26.9	16.9	21.2	24.7	97.3
Lu-177m	He-3	pn	11.5	1.86	22.2	27.2	25.3	18.1	29.6	U
Lu-176	He-3	p	7	-4.24	22.3	27.3	31.5	18.1	25.1	2.61
Yb-176	Li-7	p4n	0	28.2	30.9	35.9	7.7	33.9	33.9	12.6
Yb-174	Li-7	p2n	0	15.5	31	36	20.5	33.9	33.9	31.6
Yb-173	Li-7	pn	2.5	8.02	31	36	28.0	29.8	32.3	16.2
Yb-172	Li-7	p	0	1.66	31.1	36.1	34.4	33	33	21.9
Yb-176	Li-6	p3n	0	20.9	31.3	36.3	15.4	31.2	31.2	12.6
Yb-174	Li-6	pn	0	8.24	31.4	36.4	28.2	31.1	31.1	31.6
Yb-173	Li-6	p	2.5	0.77	31.4	36.4	35.6	31.1	33.6	16.2
Er-170	B-11	p2n	0	24.9	48.5	53.5	28.6	53.6	53.6	14.9
Er-168	B-11	p	0	11.6	48.6	53.6	42.0	53.5	53.5	27.1
Er-170	B-10	pn	0	13.4	48.9	53.9	40.5	50.9	50.9	14.9
Ho-166m	C-13	p	7	17.2	56.7	61.7	44.5	63.3	70.3	U
Dy-164	N-15	p	0	23.1	64.4	69.4	46.3	73	73	28.1
Gd-160	F-19	p	0	26.7	78.8	83.8	57.1	92	92	21.8

Table III
Production of (31-yr) Hf-178
Reactions having total input charge = 74

Reaction Target	Projectile	Emission	Target spin	Threshold energy (MeV)	Coulomb barrier (MeV)	Projectile energy (MeV)	Internal E of excitation (MeV)	Orbital momentum L-max	Channel spin h-bar	Abundanc %
W-180	n	2pn	0	14.2	0	19.2	5.0	8.3	8.3	0.13
W-182	n	2p3n	0	28.9	0	33.9	5.0	11	11	26.3
W-182	n	*alpha n*	0	0.66	0	5.66	5.0	4.5	4.5	26.3
W-183	n	2p4n	0.5	35.1	0	40.1	5.0	12	12.5	14.3
W-183	n	*alpha 2n*	0.5	6.85	0	11.8	5.0	6.5	7	14.3
W-184	n	2p5n	0	42.5	0	47.5	5.0	13.1	13.1	30.7
W-184	n	*alpha 3n*	0	14.2	0	19.2	5.0	8.3	8.3	30.7
W-186	n	2p7n	0	55.5	0	60.5	5.0	14.8	14.8	28.6
W-186	n	*alpha 5n*	0	27.2	0	32.2	5.0	10.8	10.8	28.6
Ta-180	p	2pn	8	14.1	12.1	19.2	5.0	8.3	16.3	0.012
Ta-181	p	2p2n	3.5	21.8	12.1	26.8	5.0	9.8	13.3	99.98
Ta-181	p	*alpha*	3.5	-6.45	12.1	17.1	23.6	7.8	11.3	99.98
Ta-180	d	2p2n	8	16.4	11.7	21.4	5.0	12.8	20.8	0.012
Ta-180	d	*alpha*	8	-11.9	11.7	16.7	28.6	11.3	19.3	0.012
Ta-181	d	2p3n	3.5	24.1	11.7	29.1	5.0	15	18.5	99.98
Ta-181	d	*alpha n*	3.5	-4.22	11.7	16.7	20.9	11.4	14.9	99.98
Ta-180	t	2p3n	8	22.6	11.4	27.6	5.0	18.4	26.4	0.012
Ta-180	t	*alpha n*	8	-5.64	11.4	16.4	22.0	14.1	22.1	0.012
Ta-181	t	2p4n	3.5	30.33	11.4	35.3	5.0	20.8	24.3	99.98
Ta-181	t	*alpha 2n*	3.5	2.03	11.4	16.4	14.4	14.2	17.7	99.98
Hf-182	*alpha*	2p6n	0	56.6	21.9	61.6	5.0	32.4	32.4	U
Hf-182	*alpha*	*alpha 4n*	0	28.3	21.9	33.3	5.0	23.8	23.8	U
Hf-180	*alpha*	2p4n	0	44.2	22	49.2	5.0	28.9	28.9	35.2
Hf-180	*alpha*	*alpha 2n*	0	15.9	22	27	11.1	21.4	21.4	35.2
Hf-179	*alpha*	2p3n	4.5	36.8	22	41.8	5.0	26.6	31.1	13.7
Hf-179	*alpha*	*alpha n*	4.5	8.55	22	27	18.5	21.4	25.9	13.7
Hf-178	*alpha*	2p2n	0	30.7	22.1	35.7	5.0	24.5	24.5	27.1
Hf-178	*alpha*	*alpha*	0	2.45	22.1	27.1	24.7	21.4	21.4	27.1
Hf-177	*alpha*	2pn	3.5	23.1	22.1	28.1	5.0	21.7	25.2	18.6
Hf-176	*alpha*	2p	0	16.7	22.1	27.1	10.4	21.3	21.3	5.2
Hf-182	He-3	2p5n	0	36	22.4	41	5.0	22.4	22.4	U
Hf-182	He-3	*alpha 3n*	0	7.71	22.4	27.4	19.7	18.3	18.3	U
Hf-180	He-3	2p3n	0	23.6	22.5	28.6	5.0	18.7	18.7	35.2
Hf-180	He-3	*alpha n*	0	-4.65	22.5	27.5	32.2	18.3	18.3	35.2
Hf-179	He-3	2p2n	4.5	16.2	22.5	27.5	11.3	18.3	22.8	13.7
Hf-179	He-3	*alpha*	4.5	-12	22.5	27.5	39.5	18.3	22.8	13.7
Hf-178	He-3	2pn	0	10.2	22.5	27.5	17.3	18.3	18.3	27.1

Hf-177	He-3	2p	3.5	2.55	22.6	27.6	25.1	18.3	21.8	18.6
Lu-177m	Li-7	2p4n	11.5	33.4	31.3	38.4	5.0	35.1	46.6	U
Lu-177m	Li-7	*alpha 2n*	11.5	5.09	31.3	36.3	31.2	34.2	45.7	U
Lu-176	Li-7	2p3n	7	27.3	31.3	36.3	9.0	34.1	41.1	2.61
Lu-176	Li-7	*alpha n*	7	-1.01	31.3	36.3	37.3	34.1	41.1	2.61
Lu-177	Li-7	2p2n	3.5	21	31.4	36.4	15.4	34.1	37.6	97.3
Lu-177	Li-7	*alpha*	3.5	-7.3	31.4	36.4	43.7	34.1	37.6	97.3
Lu-177m	Li-6	2p3n	11.5	26.1	31.7	36.7	10.6	31.4	42.9	U
Lu-177m	Li-6	*alpha n*	11.5	-2.16	31.7	36.7	38.9	31.4	42.9	U
Lu-176	Li-6	2p2n	7	20	31.8	36.8	16.8	31.4	38.4	2.61
Lu-176	Li-6	*alpha*	7	-8.26	31.8	36.8	45.1	31.4	38.4	2.61
Lu-177	Li-6	2pn	3.5	13.7	31.8	36.8	23.1	31.3	34.8	97.3
Yb-176	Be-9	2p5n	0	47.1	40.3	52.1	5.0	47.4	47.4	12.6
Yb-176	Be-9	*alpha 3n*	0	18.8	40.3	45.3	26.5	44.2	44.2	12.6
Yb-174	Be-9	2p3n	0	34.4	40.4	45.4	11.0	44.1	44.1	31.6
Yb-174	Be-9	*alpha n*	0	6.11	40.4	45.4	39.3	44.1	44.1	31.6
Yb-173	Be-9	2p2n	2.5	26.9	40.5	45.5	18.6	44.1	46.6	16.2
Yb-173	Be-9	*alpha*	2.5	-1.36	40.5	45.5	46.9	44.1	46.6	16.2
Yb-172	Be-9	2pn	0	20.5	40.5	45.5	25.0	44	44	21.9
Yb-171	Be-9	2p	0.5	12.5	40.6	45.6	33.1	44	44.5	14.4
Tm-169	B-11	2p	0.5	17.2	49.3	54.3	37.1	54	54.5	100
Er-170	C-13	2p3n	0	45.8	57.2	62.2	16.4	63.9	63.9	14.9
Er-170	C-13	*alpha n*	0	17.5	57.2	62.2	44.7	63.9	63.9	14.9
Er-168	C-13	2pn	0	32.5	57.4	62.4	29.9	63.8	63.8	27.1
Er-167	C-13	2p	3.5	24.7	57.5	62.5	37.8	63.8	67.3	22.9
Er-170	C-12	2p2n	0	40.8	57.7	62.7	21.9	61.2	61.2	14.9
Er-170	C-12	*alpha*	0	12.5	57.7	62.7	50.2	61.2	61.2	14.9
Er-168	C-12	2p	0	27.6	57.9	62.9	35.3	62.1	62.1	27.1
Ho-166m	N-15	2pn	7	35.6	65.2	70.2	34.6	73.6	80.6	U
Ho-165	N-15	2p	3.5	29.3	65.3	70.3	41.0	73.5	77	100
Ho-166m	N-14	2p	7	24.8	65.7	70.7	45.9	70.9	77.9	U
Dy-164	O-18	2p2n	0	47.5	72.2	77.2	29.7	85.9	85.9	28.1
Dy-164	O-18	*alpha*	0	19.2	72.2	77.2	58.0	85.9	85.9	28.1
Dy-163	O-18	2pn	2.5	39.8	72.3	77.3	37.5	85.9	88.4	24.9
Dy-162	O-18	2p	0	33.5	72.4	77.4	43.9	85.8	85.8	25.5
Dy-164	O-17	2pn	0	39.4	72.6	77.6	38.2	83.2	83.2	28.1
Dy-163	O-17	2p	2.5	31.8	72.8	77.8	46.0	83.2	85.7	24.9
Dy-164	O-16	2p	0	35.3	73.1	78.1	42.8	80.5	80.5	28.1
Gd-160	Ne-22	2p2n	0	56.7	86.1	91.1	34.4	105	105	21.8
Gd-160	Ne-22	*alpha*	0	28.4	86.1	91.1	62.7	105	105	21.8
Gd-158	Ne-22	2p	0	43.3	86.3	91.3	48.0	104.8	104.8	24.8
Gd-160	Ne-21	2pn	0	46.3	86.5	91.5	45.2	102.2	102.2	21.8
Gd-160	Ne-20	2p	0	39.6	87	92	52.4	99.5	99.5	21.8
Sm-154	Mg-26	2p	0	53.3	99	104	50.7	123.3	123.3	22.6
Nd-150	P-31	2pn	0	70.8	118	122.9	52.1	148.7	148.7	5.6
Xe-136	Ca-48	2p4n	0	127.5	136.3	141.3	13.8	205.9	205.9	8.9

Xe-136	Ca-48	*alpha 2n*	0	99.2	136.3	141.3	42.1	205.9	205.9	8.9
Xe-134	Ca-48	2p2n	0	113	136.7	141.7	28.7	205.6	205.6	10.4
Xe-134	Ca-48	*alpha*	0	84.7	136.7	141.7	57.0	205.6	205.6	10.4
Xe-132	Ca-48	2p	0	98.1	137.1	142.1	44.0	205.3	205.3	26.9
Xe-136	Ca-46	2p2n	0	110.2	137.1	142.1	31.9	201	201	8.9
Xe-136	Ca-46	*alpha*	0	82	137.1	142.1	60.1	201	201	8.9
Xe-134	Ca-46	2p	0	95.8	137.5	142.5	46.7	200.7	200.7	10.4
Te-130	Ti-50	2p	0	103.3	144.8	149.8	46.5	215.8	215.8	34.5
Sn-126	Cr-54	2p	0	107.5	151.1	156.1	48.6	230	230	U